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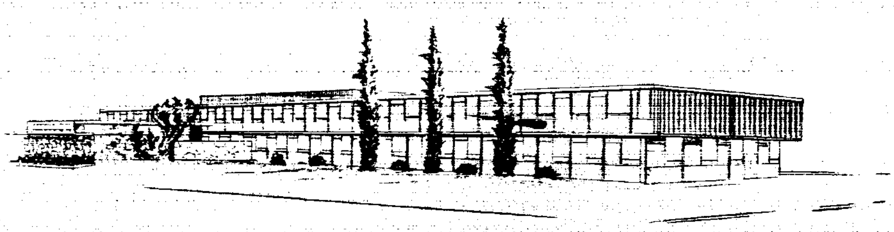

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AN INVESTIGATION OF THE PHENOMENA OF IMPACT FLASH AND ITS POTENTIAL USE AS A HIT DETECTION AND TARGET DISCRIMINATION TECHNIQUE*

by

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ABSTRACT

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This paper will present the results of an experimental research program to provide data on the impact radiation associated with the collision of a projectile and a target. More specifically, this paper will analyze the phenomena of impact flash and examine its potential use in two areas: (1) Estimation of the impact flash likely to be observed on impact of a lunar probe on the moon's surface, and correlation of impact flash measurements made of an actual lunar impact with physical characteristics of the lunar surface; (2) Selection of hypervelocity impact flash phenomena, which may be remotely observed and which could provide significant information for determining the occurrence of a collision, the damage inflicted upon the target (satellite, ICBM, decoy, etc.) and possibly the identification of the target material.

The program consisted of a parametric study involving the variables associated with the impacting projectile against various targets, some designed to simulate the lunar surface. The tests consisted of firing projectiles of varied mass, material, diameter and velocity into targets under various ambient conditions. Observations were made and quantitative data obtained for the magnitude of the luminosity of the impact flash, the total radiated power, the duration of the flash, and the spectrum of emitted light.

AUTHOR

INTRODUCTION

The research program to be described in this paper was directed toward the possibility of identifying the impact of a projectile or probe on a target surface and the techniques required for identification of the target material. The program, therefore, was conducted with the specific goal of permitting recommendations to be made as to the observations and techniques which can be carried out from a remote position to answer the important questions related to the impact phenomena.

When a projectile strikes a target, it will: (1) generate an intense flash of light; and (2) form an impact crater.[1] It was believed that if either or both of these reactions were of sufficient magnitude, they could be observed here on earth. Specifically, whether or not a lunar probe (or meteor) can cause an impact flash of sufficient magnitude will be estimated on the basis of the experimental results to be reported in this paper. In contrast to the Russian observations,[2] astronomers have attempted for years to observe the impact of meteors on the moon[3-6] without drawing any significant conclusions. Experimental researchers have also attempted to look at the phenomena of impact flash[7,8] and cratering in rocks,[9,10] but under conditions which may be inapplicable to the investigation of lunar impact flash or spacecraft hit detection and discrimination. For this reason, the GM Defense Research Laboratories, General Motors Corporation, undertook a program to determine some specific features of an impact flash and, generally, to determine the reaction of a target to a relatively high-velocity projectile. Results of this program may make it possible to identify an impact and to discover the material composition of the lunar surface or target vehicle. Whether or not the impact of a projectile will provide this information depends upon the peak intensity of the flash, the duration of the flash, and the spectral distribution of light in the flash. If these aspects of the phenomena are known, it will be possible to design instruments for recording the flash and to estimate whether or not data from these instruments will provide a record of the conditions of the impact. Also, it may be possible, by the proper choice of materials from which the projectile is made, to augment the chances of success in the test by increasing the luminosity of the flash. Therefore, the experiments were designed to permit observations and to describe quantitatively the phenomena of impact flash; i.e., peak luminosity, time duration, and the spectrum of light emitted upon impact of a high-velocity projectile upon a target surface.

The first spatial environmental condition to be considered is the effect of the gas density surrounding the target's surface. Most experiments on high-speed impact have been made with gas at appreciable pressure; that is, many orders of magnitude greater than pressure near the lunar surface or at extreme altitudes. Consequently, it is essential to learn the effect of the gas on impact flash if results of laboratory experiments to predict the phenomena of impact flash on the moon are to be used. Early work at the University of Utah[8] indicated that the gas surrounding the target played an important part in producing the impact flash. This conclusion was based on the observation, in metal-to-metal impact, of a line spectrum attributed to the reaction of the surrounding gas with a high-velocity spray thrown out of the crater during the crater's formation. Therefore, it may be concluded that an impact on an atmosphere-free moon would not cause a flash. These conclusions will be shown to be not applicable to the case in point, since both the early experiments by the NASA-Ames Labs[1] and the tests to be described herein show that impact flash is obtained under reduced ambient gas pressures.

The second spatial environment condition to be considered is that of materials. Satellites, ICBM s, decoys, etc. are fabricated from standard known structural materials; e. g., aluminum, magnesium, steel, etc. The composition of the lunar surface, however, is uncertain. Knowledge here is confused by contradictions found in hundreds of papers published on the subject. Suffice to say, the majority of references agree that the rough and cratered lunar surface was caused by the impact of meteors occurring over the eons following the solidification of the entire lunar mass. According to currently accepted views, the moon's surface is a rocky rubble covered with a thin layer of dust[11], its composition and character undoubtedly varying from place to place and including, perhaps, steep slopes of bare rock in the mountainous regions.

The other environmental conditions to be considered are those relating to the projectile or the lunar probe. The probe will have a given size, be made of a certain material, and strike at a specified velocity. It should be noted that the Ranger vehicles will impact the moon at a velocity close to 10,000 ft/sec--a speed easily attainable in the laboratory. The vehicles will be made of metals and plastics; these also can be duplicated in the laboratory. On the other hand, the vehicle will weigh more than 700 pounds, and projectiles of this weight are beyond the capability of the tests in this program. Accordingly, part of the investigation will be concerned with projectiles of different sizes to determine scaling laws for extrapolating the results of the laboratory to the conditions of full-scale flight.

Velocity will also be a factor in evaluating satellite impact conditions; therefore, laboratory tests involving velocities up to 27,000 ft/sec will be carried out to evaluate velocity scaling effects.

RANGE AND MONITORING INSTRUMENTATION

The tests were conducted in the Ballistics Range which is partially described in GM, DRL Report No. ER 62-201 and Reference 12. The basic equipment consists of a gun, a flight range and an impact chamber. The projectile is launched down range by either of two guns: using either a 0.22-inch or 0.30-inch launch tube or accelerated-reservoir, light-gas gun (AR-LGG); or a 0.22-inch Super Swift smooth-bore rifle. The choice of guns depends on the desired projectile mass and velocity (Figure 1). The 0.22-inch AR-LGG (Figure 2) may be fired horizontally at velocities in the order of 27,000 ft/sec while the Super Swift is used horizontally or vertically when the velocity requirement does not exceed 10,000 ft/sec (Figure 3). The vertical firing capability of the Super Swift gun is especially useful when nonsolid targets such as sand or crushed stone are used. In these cases no alien binders are required to maintain the target shape.

During the course of flight, the model's position and time of flight are recorded at both of two spark shadowgraph stations in an instrumented velocity chamber (Figures 3 and 4). Figure 4 is a schematic of the instrumentation associated with each station. When the model interrupts the photobeam, electronic counters are started and a short-duration spark exposes a film plate. Figure 5 is a shadowgraph which shows a spherical model separated from its sabot at a velocity of 21,000 ft/sec. These measurements of time and distance of the projectile between stations serve to determine velocity along the trajectory and, in particular, at the target. The accuracy of the impact velocity determined in this manner is within 0.1 percent.

The model flight terminates in a specially constructed impact chamber (Figure 2) which has a multitude of viewing ports. The rear wall of the chamber, a full-size door, allows easy insertion and removal of the targets. The targets are held by a mount attached to the floor of the chamber. The impact and velocity chambers are vacuum sealed and can be pumped down to less than one micron of mercury. Air or any desired gas mixture can be introduced into the chamber as a test medium. An Alphatron vacuum gauge and mercury manometers provide accurate and reliable pressure measurement.

Photographic and photoelectric equipment, and open-shutter cameras with black-and-white and/or color film, have been used to monitor the impact flash. Because initial records showed evidence that radiation from the impact flash lay in the visible and near infrared, quantitative optical monitoring devices were chosen for their response to these wave lengths. Two photomultiplier tubes were used to record peak luminosity and total time duration of emitted light--a PM tube (Dumont Type 6911) sensitive to infrared radiation from 4,500 Å to 10,000 Å, and a second tube (Dumont Type 6292) sensitive to the visible spectrum from 3,500 Å to 5,500 Å. The PM tubes were calibrated to measure radiance in watts per solid included angle.

RESULTS AND ANALYSIS

The experiments have been conducted with projectiles of the following materials: nylon, aluminum, pyrex, brass, steel, magnesium and silver. The projectiles were spherical in shape and ranged in diameter from 1/32 to 3/16 inch and were launched at velocities ranging from 4,000 to 23,000 feet per second.

The majority of the tests were conducted using sand or granite targets. The sand, commercially known as "Nevada 135", was a fine-grade silicon sorted through a 100-mesh screen and retained on a 200-mesh screen. The granite was commercially known as "Georgia Grey". In order to establish the effects of certain other variations, a number of rounds were fired into aluminum targets. The projectiles and targets tested were systematically varied to cover the observables of interest. The results of the experiments within the framework of this system are reported below.

Within the range of the experiments, an impact flash was observed under all conditions. A typical impact flash observed by an open-shutter camera is shown in Figure 6. A study of more than 100 records of impact flashes shows that the intense luminosity in the center of the impact is associated with both the projectile and the area of the target under the projectile, while the striated luminosity surrounding the point of impact is associated with the debris ejected from the crater. These conclusions are in agreement with the flash pictures obtained at the Ames Research Laboratories[1]. Open-shutter flash pictures, shown in both References 1 and 8, depict a dark spot surrounded by an intense impact flash in the center of the impact. The dark spot is believed to be the opaque copper projectile used in those tests. The pictures shown in Figure 6, however, were taken of a translucent (nylon) projectile; hence, the dark spot does not appear. Typical craters formed in both sand and granite targets are shown in Figure 7.

EFFECT OF AMBIENT GAS AND PRESSURE

Since the impact of a lunar probe will occur in the absence of any atmosphere, it was necessary to test the effect of various ambient gases and gas pressures on the magnitude of the impact flash. In pilot experiments, nylon spheres were fired into sand targets under conditions of varying velocity and varying ambient air pressures (Figure 8). The ordinate in this figure is the peak luminosity of the flash, I_{np} (in watts per steradian), which is equal to the measured value normal to the target surface. In Figure 8, the peak luminosity, I_{np}, is then plotted as a function of both impact velocity and ambient range pressure. In Figure 11a, three selected impact velocities were chosen and the values of I_{np} corrected to a best-fit slope of the data. These three velocities were then made the dependent variable and the data points replotted as a function of ambient pressure. An important result of the research program is demonstrated by Figure 11b. At ambient pressures of 10 mm of Hg and down to 42 microns (nearly three orders of magnitude change in pressure), the magnitude of the peak luminosity of the impact flash did not vary significantly. Extrapolation of these data to lower pressures would indicate that the flash is independent of the surrounding pressure.

To demonstrate further this important observation, two shots (not shown on plot) were fired in an atmosphere of He (a "dark" gas)--one at 76.0 mm pressure, and one at 4.0 mm pressure. Even in the He atmosphere, the monitored flash was identical to that obtained in air and was independent of ambient pressure.

EFFECT OF VARYING PROJECTILE PARAMETERS AND TARGET MATERIAL

In order to test the relationship of the impact flash to the many possible projectile parameters, experiments were made in which the size, material, and velocity of the projectile varied. The targets used in these tests consisted of either sand or granite held in a target fixture. Some of the results of these tests have already been observed in Figure 8a, which shows the intensity of impact flash increasing with projectile velocity. Within the nominal scope of the data obtained thus far, the intensity appears to increase as some power of the impact velocity (v^n).

With nylon projectiles against sand targets, the data of Figure 8b show that I_{np} varies as velocity is raised to the 4.0 power ($v^{4.0}$). This relationship of I_{np} to impact velocity is further tested by the data shown in Figures 9, 10 and 11a. Using aluminum and glass projectiles to impact sand (Figure 9), and aluminum projectiles against granite (Figure 10), I_{np} can be seen to vary as $v^{3.88}$ and $v^{4.96}$, respectively. In Figure 11a, the data obtained from steel projectiles against sand targets indicate that I_{np} varies as $v^{8.30}$. Although the exact power relationships cannot yet be determined, it is anticipated that the exponent of velocity will lie between 3 and 9 for a variety of projectile sizes and materials against either sand or rock targets.

In addition to the velocity scaling effects, a third important conclusion is demonstrated in Figure 11. From Figure 11a, values of I_{np} were taken from the plot for the case of four sizes of steel projectiles impacting sand targets at a constant velocity of 8,000 ft/sec. These four values of I_{np} were then replotted as a function of projectile diameter as shown in Figure 11b. A method of least square fit was then applied to these data points, with the result that the best fit of the data showed I_{np} to vary as the squqre of the projectile diameter (D_p). This technique was also applied to the data for two sizes of both glass and aluminum projectiles; again, I_{np} can be shown to vary as $D_p^{\,2}$. The graphs summarizing the relationship of I_{np} to $D_p^{\,2}$ are given in Figure 14.

At this point, an empirical relationship (neglecting target material) to describe the results thus far can be written as:

$$I_{np} = CAv^n \quad \dots\dots\dots\dots\dots\dots \quad (1)$$

where

	I_{np}	=	peak luminosity (visible)
	A	=	area of projectile on target surface
	v	=	velocity of impacting projectile
	n	=	velocity exponent $3 \leq v \leq 9$
	C	=	a constant

Typical values of n and C for specific impact conditions are given in Table I.

TABLE I

Values of Terms in Equation 1

Projectile	Target	C $\frac{\text{watts per } 4\pi \text{ sterad}}{\text{ft}^2 \quad (\text{fps})^n}$	n	Photo-multiplier
Aluminum	Granite	0.743×10^{-9}	3.88	Visible
Aluminum	Sand	0.312×10^{-14}	4.96	Visible
Steel	Sand	0.380×10^{-27}	8.30	Visible
Glass	Sand	0.613×10^{-14}	4.96	Visible
Nylon	Sand	0.447×10^{-11}	4.02	Infrared

Equation 1 suggests that the impact flash is a phenomenon associated with the surface area of the projectile rather than with its mass. If this is correct, it can be concluded that projectiles of the same surface area and material would give the same impact flash, even if their total masses differed due to dissimilar internal construction. To investigate this point, hollow and solid brass spheres of the same diameter (1/8 inch) were fired at the same velocity against sand targets. The surface areas of the two spheres were identical, of course, but the difference in mass between the two was 40 percent. Result: the peak luminosities of impact flashes differed by less than 10 percent, and time duration of the two flashes was almost equal. This experiment supports the contention that Equation 1 is a correct representation of the peak luminosity of impact flash.

The coefficient C may be a function of the materials from which the projectile and target are made. The experiments show that this is, in fact, the case. The values of C are listed in Table I.

Figure 13 shows that a constant projectile with a change of target material produces a variation in impact flash; for example, the peak luminosity of the impact flash in granite is more than ten times that in sand. Also, over the range of velocities of interest here, the data are represented reasonably well by a variation of peak luminosity, with approximately the fourth power of the velocity for granite, and the fifth power of velocity for sand targets.

DURATION OF IMPACT FLASH

In previous discussion, only the peak luminosity associated with impact flash--not the integrated total luminosity over the time of emission--has been of concern. It was interesting to learn the instant that the flash occurred with respect to moment of impact, and to relate the duration of the flash to the elapsed time of projectile penetration and crater formation. Available references (see, for instance, References 1, 9 and 13) show that behavior of the projectile and the mechanism of the crater's formation vary, depending upon such factors as the velocity of impact and the relative strength of the specific projectile-target combination. It was suspected, therefore, that the initial peak luminosity was associated with the penetration of the more-or-less-intact projectile, and the trailing off of the flash with the deformation of the projectile and the expansion of the crater. This hypothesis is consistent with the greatly increased duration of the flash with a granite target as compared to the shorter duration of the flash with a sand target. Several typical oscilloscope traces of the pulse of luminosity, observed by a photomultiplier tube, can now be examined.

The variation of luminosity with time is shown for three typical impact conditions in Figure 13. The case of a hard projectile striking a soft target is illustrated by the top trace of a steel sphere impacting a sand target. There are two distinct phases in the generation of the impact flash. A sharp peak appears first, lasting in this case less than a microsecond, followed by a long, low-intensity tail lasting many microseconds. Records with a high-speed framing camera show that the impact flash begins almost as soon as the projectile contacts the target; the peak is thus associated with the initial phase of penetration and cratering. For the case in question, the peak lasts less than the time it takes the projectile to penetrate the target to a depth equal to its own diameter.

The case of an aluminum projectile striking a sand target is shown by the center trace. The first part of the peak lasts about the same time as in the case of the steel projectile. This initial peak is followed by a region in which the light decays from 0.5 to 0.1 of peak value in approximately 3 microseconds, due, perhaps, to the increased deformation of the aluminum projectile as compared to that of the steel projectile.

This point is borne out by the variation in luminosity, with time for the impact, of an aluminum projectile into a granite target as shown in the bottom trace. The entire peak region of the flash is now seen to be broadened. The time from the initial rise through the decay to 0.1 of peak value lasts nearly 5 microseconds. The case of aluminum into granite at 8,400 ft/sec begins to approach the fluid impact region; a crater is formed in the initial instance of impact and material is jetted from the periphery of this initial crater at very high velocity.

Consequently, a surface of highly-shocked material is exposed during the initial phase of cratering. The intensity of the shock conditions are greatest at the beginning of impact and diminish as the shock phenomena decrease with the increasing volume of material affected by the growing crater and expanding wave phenomena. The combination of these two effects produces the elongated shape of the light pulse seen in the case of aluminum into granite. In contrast to this, the case of steel into sand is probably close to the region of unbroken projectile impact, and the short light pulse might indicate that highly-shocked material is generated only during the moment of initial penetration. The case of aluminum into sand is probably an intermediate case, somewhere between the unbroken projectile and the fluid impact cases.

Two additional experiments substantiate the fact that the luminosity occurs at the instant of impact and persists for only a very brief period. In the first experiment, the Beckman & Whitley high-speed framing camera was used to observe several projectile-target collisions. A typical framing sequence (Figure 14) shows the projectile to have moved approximately 0.5 inch to impact the target, then the flash occurs in a single frame and is extinguished in a total time of less than 2.4 microseconds.

In the second experiment, aimed at demonstrating the short duration of the flash, 3/16 inch aluminum projectiles were fired at an average velocity of 17,600 ft/sec against varying thicknesses of titanium sheets. Three sheet thicknesses were tested--0.012 inch, 0.020 inch, and 0.040 inch--and the measured peak luminosities were 523, 505, and 543 watts/steradian, respectively. These data show that the peak luminosity is unaffected by the thickness of the target and that the impact flash is produced on, or very near, the surfaces of the projectile and the target (collision interface).

SPECTRUM OF AN IMPACT FLASH

To permit a more complete description of the phenomena of the impact flash, it was necessary to observe the spectrum of the emitted radiation. From an analysis of the spectra obtained under varying conditions of impact, it is anticipated that the composition of an unknown target might be determined.

Only a few spectra have been observed to date, but the results are most interesting. Two typical spectrograms, obtained from the impact of a nylon cylinder against both an aluminum and a sand target, are shown in Figures 15 and 16. Figure 15 is the result of the fairly intense flash generated by a nylon cylinder impacting on an aluminum target at 24,600 ft/sec. The aluminum doublet at 3,950 Å appears in the near ultraviolet on the right side of the figure, and the aluminum oxide bands appear between the blue and the green. There is a continuum extending from the near infrared to the green, and the sodium D line appears strongly. (The short line segments are, of course, the image of a point-source mercury calibration which serves also to locate the point of impact along the vertical axis of the film.) The appearance of the aluminum oxide bands in the spectrum shown in Figure 15 suggests an apparent anomaly, when compared with the data of Figure 8 which show the impact flash to be independent of the ambient gas and the surrounding gas pressure. It is believed, however, that the oxide bands appear as a result of surface oxidation on the unpolished surfaces of both projectile and target.

The second typical spectrograph (Figure 16) is the result of a relatively weak flash generated by a nylon cylinder impacting a sand target at approximately 10,000 ft/sec. The intensity of the flash, so far below the demands of the spectrograph, made it necessary to superimpose the flash of ten successive rounds in order to obtain a legible record. Although the photographic quality of the resulting spectrograph leaves much to be desired, it seems clear that a line spectrum is not generated--rather, there is a continuum in the near infrared. On the basis of Figure 16, it would be difficult to determine the atomic and molecular composition of a sand target, though the line and band spectra may be present but too weak to be discernible. Further measurements with a more sensitive instrument are needed to investigate this possibility.

DISCUSSION OF EXPERIMENTAL RESULTS

Referring to the data given in Figure 8-12, the luminosity-versus-time plots of Figure 13, and the empirical relationship given in Equation 1, the phenomena which have been observed can be defined as below.

The appearance of an intense flash of light upon impact of a projectile is a result of the conversion of mechanical energy to light. Most certainly the energy of the projectile is expended in a number of possible reactions: heat is generated, radiation is emitted (possibly over the spectrum from gamma rays to microwaves), and mechanical work is done in forming the impact crater. These experiments, however, were concerned with monitoring only that portion of the projectile energy which appears as visible light. It is reasonable to assume that the magnitude of radiated visible light will be a function of the energy of the impacting projectile.

Since the target reacts to the impact in a manner dictated by the magnitude of the pressure pulse, it may also be reasonable to relate the intensity of impact flash to the properties of the materials after being shocked due to the collision; however, a process by which luminosity is derived from the rapid application of pressure is unavailable. Thus, a causal relationship between impact-generated pressure and luminous radiation cannot be established by these experiments. More complex, and much more difficult to define, are the excitation energy of atoms under compressions, and the multiple-electron problem which is a result of the many possible ways in which electrons of different binding energies may react. Therefore, the present analysis is restricted to the establishment of an empirical relationship (Equation 1) to describe the phenomena and to estimate the intensity of impact flash.

OBSERVATIONS OF LUNAR IMPACT

In applying the results of laboratory tests to observations of lunar impact by instruments placed on the earth, two cases will be considered: (1) the crash landing of a Ranger lunar probe (at lunar escape velocity), and (2) the impact of a marble-sized meteoroid. The question is whether or not a discernible record of the impacts of these objects can be obtained from the accompanying flash of light.

The answer to this question is critically dependent upon the design and sensitivity of the recording instrument. A full treatment of the subject is beyond the scope of this paper, and the discussion will be restricted to a limited study of two examples. The intent here is to present a method of analysis and to give a rough indication of possible answers .

Any earth-placed instrument will see the flash of the impact against the background intensity of the lunar surface. This background intensity represents noise on the record, and ability to "see" the flash will depend on whether or not the flash is distinct from the background noise. The first step in the analysis is to obtain an estimate of the lunar background intensity.

In computing the lunar background intensity, only the positions of conjunction (moon and sun in the same direction from the earth--dark of the moon) and opposition (moon and sun in opposite directions from the earth--full moon) will be analyzed. In opposition, the moon is illuminated by light from the sun with an irradiance of 140 watts/sq ft[14].

Considering a small, flat, diffuse area of lunar surface, it is easily seen that the intensity of reflected light along a normal to the surface is

$$I_N = \frac{\bar{a}\, I_R}{2\pi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $\bar{a}$ is a normal albedo which may be taken as approximately 0.1. Substitution into this equation establishes the luminous intensity of the moon to be 2.2 watts/sterad sq. ft. when the surface is in full sunlight (opposition). By a similar analysis, it can be established that when the moon is illuminated only by light reflected from the earth (conjunction), the solar irradiance is decreased to about 0.002 watts/sq ft, giving a reflected intensity of 3.0×10^{-5} watts/sterad sq. ft. Part of the problem is thus to establish the feasibility of observing a given impact flash against this background radiation.

The next step in the analysis is to estimate the intensity of the flash from the impact. The Ranger lunar probe is taken to be a vehicle of aluminum with a projected area of 19.6 sq.ft., an effective length of 2 ft., and an impact velocity of 8,000 ft/sec. The lunar surface may be either sand or granite. The intensity of the flash is calculated from Equation 1 using Table 1.

The effective duration of the flash, $\bar{t}$, is estimated to be the time it takes the probe to travel one-half its length; $\bar{t}$ is used to compute the total light from relation

$$\int I_n \, dt = I_{np} \cdot \bar{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The results of these estimates are summarized in Table II.

TABLE II

Predicted Impact Flash for Ranger Lunar Probe

Surface	I_{np} w/sterad	$\bar{t}$ sec	$\int I_n \, dt$ w sec/sterad
Sand	1.1×10^{5}	1.3×10^{-4}	14
Granite	1.6×10^{6}	1.3×10^{-4}	200

The meteoroid may be either stone or iron and will be approximated by glass (for stone) and steel (for iron). Since the experimental data have been derived from a sand target for glass and steel projectiles, estimates of the impact flash can be made only for a lunar surface of sand. The meteoroid is taken to be a sphere 1/2 inch in diameter striking at 78,000 ft/sec.

TABLE III

Predicted Impact Flash for 1/2-Inch Meteoroid

Type	Surface	I_{np} w/sterad	$\bar{t}$ sec	$\int I_n \, dt$ w sec/sterad
Stone	Sand	1.2×10^9	0.3×10^{-6}	330
Iron	Sand	1.7×10^9	0.3×10^{-6}	450

The next step requires specification of the observing instrument. The two examples considered here are telescopes equipped with: (1) a movie camera and (2) a photocell that measures the intensity of light. In example (1), continuous observation can be made by using two cameras, one recording while the other changes film.

The performance of either instrument will depend on its sensitivity and on the signal-to-noise ratio. The question of sensitivity involves a consideration of the instrument's design that is beyond the scope of this discussion. The signal-to-noise ratio also depends on the design of the instrument, but it is possible to treat this subject in a broad way for classes of instruments which depend upon the physical quantity measured. Two classes are represented by our examples. Leaving the question of sensitivity to be answered separately, certain conclusions concerning the possibility of observing the impact can then be drawn.

For the example of the telescope equipped with a movie camera, the impact flash will be recorded by a darkening of the film due to the increase in light at the point of impact. The question, then, is whether or not the dark "spot" can be distinguished from the background. The contrast between the spot and the background on the negative will depend on the ratio of the total lumens produced by the flash to the lumens falling on a corresponding area of the background during the exposure time, Δt, of the camera. The signal-to-noise ratio is determined by this ratio, namely

$$\frac{\text{signal}}{\text{noise}} = \frac{\int I_{np}\,dt}{I_N \,\sigma A \,\Delta t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where I_N is the intensity of light from the lunar surface, and A is the area of the moon's surface that corresponds to the area of the impact flash. If the flash area is smaller than the minimum resolvable area of the instrument--considered to be the case here--the correct area to take is believed to be this minimum resolvable area; namely,

$$\sigma A = \frac{\pi}{4} \left(\frac{5}{4} \frac{\lambda}{d} R \right)^2 \quad \ldots\ldots\ldots\ldots (5)$$

where λ = wavelength of the light

d = aperture of the telescope

R = distance from the earth to the moon

Considering a telescope with an aperture of 12 inches and taking green light as representative, $\lambda = 2 \times 10^{-5}$ inches. Under these conditions, $A = 5 \times 10^6 \text{ ft}^2$.

Considering also that the exposure time of the movie camera attached to the telescope is 0.1 second,

Δt - 0.1 sec.

Now the signal-to-noise ratio for various conditions of impact being investigated can be determined. This ratio is given in the following table:

TABLE IV

Observation of Lunar Impact with Telescope

Lunar Surface	Object	Signal/Noise Full Moon	Signal/Noise Dark Moon
Sand	Ranger probe	0.00002	1.3
Granite	Ranger probe	0.00026	19.1
Sand	Stone meteoroid	0.00043	31.4
Sand	Iron meteoroid	0.00058	42.8

Table IV shows that on the basis of signal-to-noise ratio, a 12-inch telescope with a 0.1-second exposure camera will not produce a discernible record of the flash from the impact of either the Ranger probe or the 1/2-inch meteoroid on the bright side of the moon (at full moon). On the other hand, there is the distinct possibility that a record could be made of the impact of either probe or meteoroid on the dark side of the moon (at opposition). Whether or not a photographic record could actually be made will depend upon questions of sensitivity and other factors, including frequency of occurrence as in the case of meteoroids. This is a subject for future investigation.

For the example of the telescope equipped with a photocell for continuous monitoring of the total light received by the telescope, the peak intensity of the impact flash will increase the background signal produced by the light received from the lunar surface. This background signal will depend on the angle of view of the telescope as determined by the area of the moon's surface to be observed, A_o. The signal-to-noise ratio is thus given by

$$\frac{\text{signal}}{\text{noise}} = \frac{I_{np}}{I_N A_o} \qquad (6)$$

For this example, the angle of view will be arbitrarily selected as two minutes of arc, which corresponds to a circular surface on the moon with a diameter of 135 miles and an area of 3.9×10^{11} sq. ft. The signal-to-noise ratios for the various conditions of impact are listed in the following table.

TABLE V

Observation of Lunar Impact with Photocell

Lunar Surface	Object	Signal/Noise Full Moon	Signal/Noise Dark Moon
Sand	Ranger probe	1.3×10^{-7}	1.0×10^{-2}
Granite	Ranger probe	1.9×10^{-6}	1.4×10^{-1}
Sand	Stone meteoroid	1.4×10^{-3}	1.1×10^{2}
Sand	Iron meteoroid	2.0×10^{-3}	1.4×10^{2}

Table V shows much the same thing as Table IV. Impacts on the bright surface of a full moon could not be distinguished from the background. On the other hand, the impact of a meteoroid on the dark side could readily be recorded. In contrast to the previous example, however, the 2-minute telescope could not "see" the impact of the Ranger probes even on the dark moon.

There is one obvious improvement in technique which should be mentioned, since it may have a bearing on the conclusions drawn from these estimates of the performance of the 2-minute telescope with continuous photocell monitor. The duration of the flash is very short, lasting only about 0.1 millisecond in the case of the Ranger probe. This suggests that the photocell circuit should be provided with a filter passing only high-frequency signals (above 1,000 cycles per second). The background signal should be greatly reduced by this technique and the signal-to-noise ratio improved accordingly. Again, the improvement realized in this manner is a subject for future investigation.

CONCLUSIONS

Although there is available an extremely limited amount of data with respect to the phenomena of impact flash, and, more important, no definitive theory to relate the generation of a flash to the mechanics of impact, certain conclusions may be drawn concerning the feasibility of observing impacts of meteoroids and space probes on the lunar surface.

(1) In all cases of impact above velocities of about 6,000 ft/sec., an impact flash was observed regardless of projectile and target material.

(2) Although tests were conducted only with air at pressures ranging from 0.040 to 80.0 mm Hg, and with helium at pressures of 76.0 and 4.0 mm Hg, there appears to be no significant effect of the composition or the pressure of the gas surrounding the impact area on the magnitude of the impact flash. This being the case, it is highly probable that a flash will occur in the case of a lunar impact at a velocity greater than 6,000 ft/sec.

(3) An empirical fit of the luminosity data indicates that the peak luminosity varies with the presented area of the projectile and with a power of the velocity that ranges between 3 and 9, depending upon the

materials of the projectile and the target. The constant of proportionality between the peak luminosity and the product of the projectile area with a power of the impact velocity also depends on the materials of both projectile and target.

(4) Examination of high-framing-rate camera records and photocell records show that the flash starts with the contact of the projectile on the target and rises to peak value during the first part of the impact process. The flash appears to be closely associated with the surface of the material that is highly shocked in the initial phase of the impact. The time duration of the flash varies markedly with changes in materials of projectile and target, particularly the latter.

(5) The spectrograms indicate that only a continuum, rather than a distinct atomic line spectra, is obtained under conditions of impact on sand targets below 10,000 ft/sec.

(6) To record the impact of a space probe or a meteoroid on the surface of the moon by observations made from the earth, a very limited study indicates the possibility of doing so if the impact takes place on a "dark" moon (illuminated by earthshine only). But if the impact occurs on the bright surface of a full moon, recording the impact by earth observations would appear to be a most difficult task.

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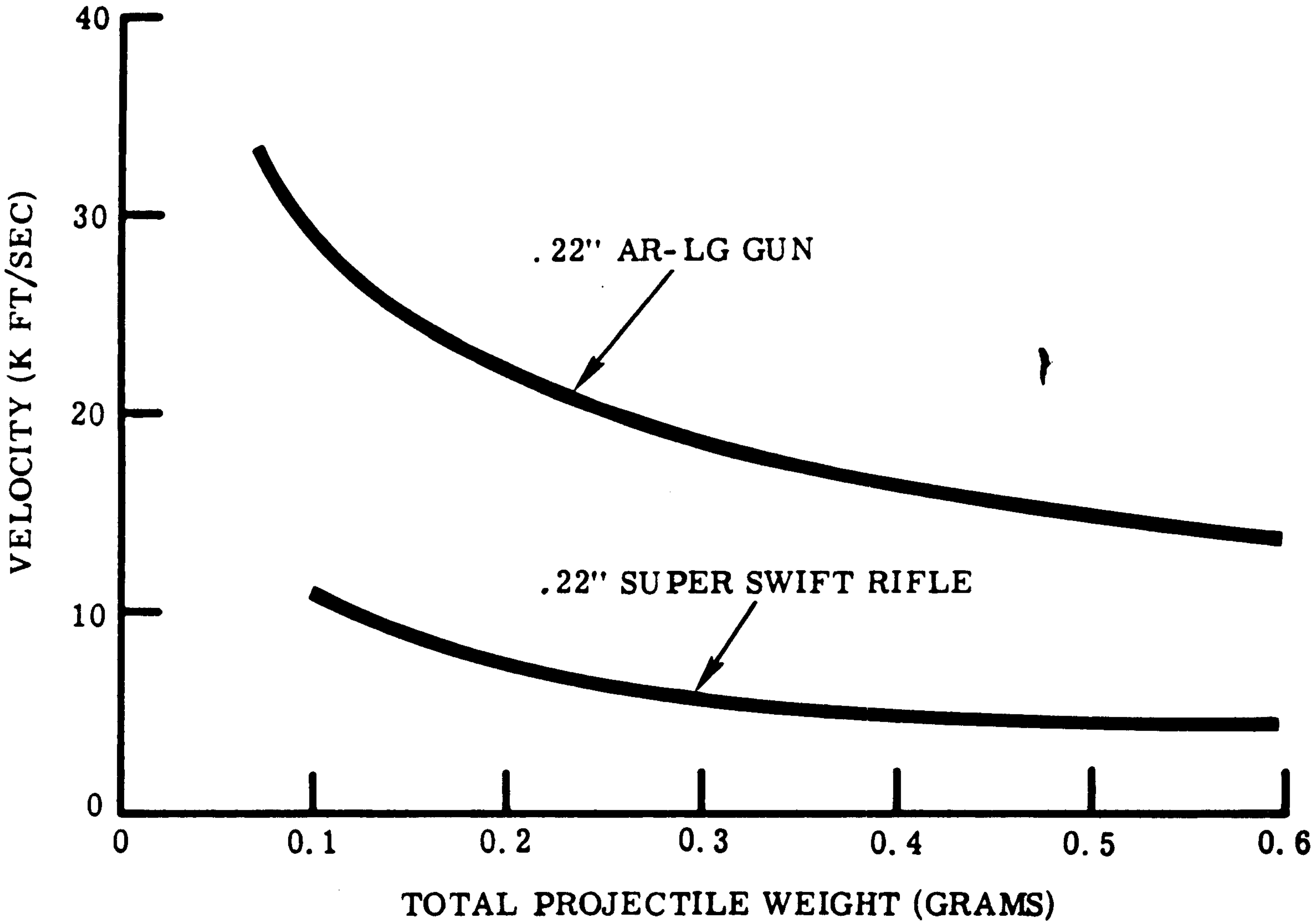


Figure 1 Summary of Launcher Performance

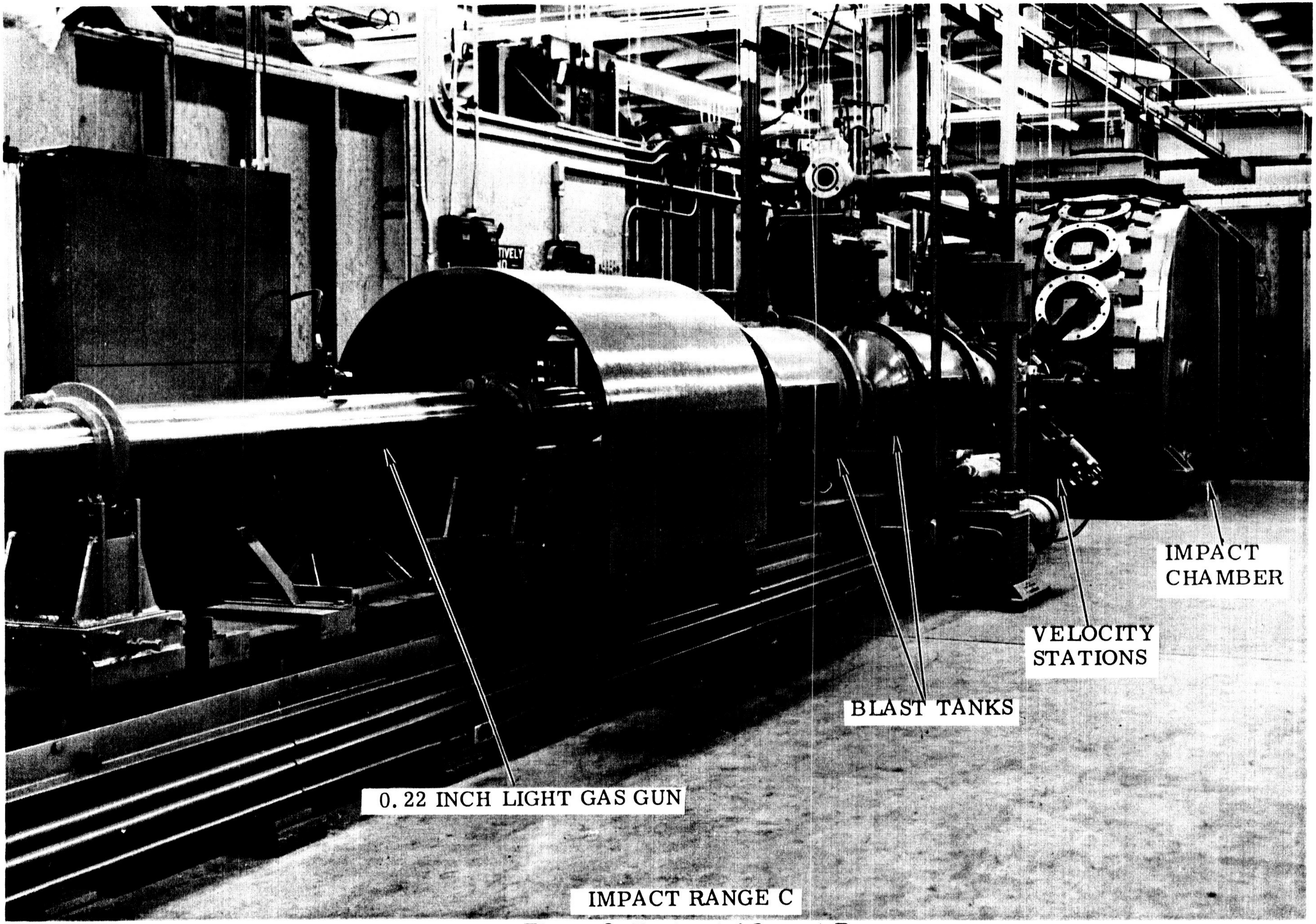


Figure 2 Horizontal Impact Range

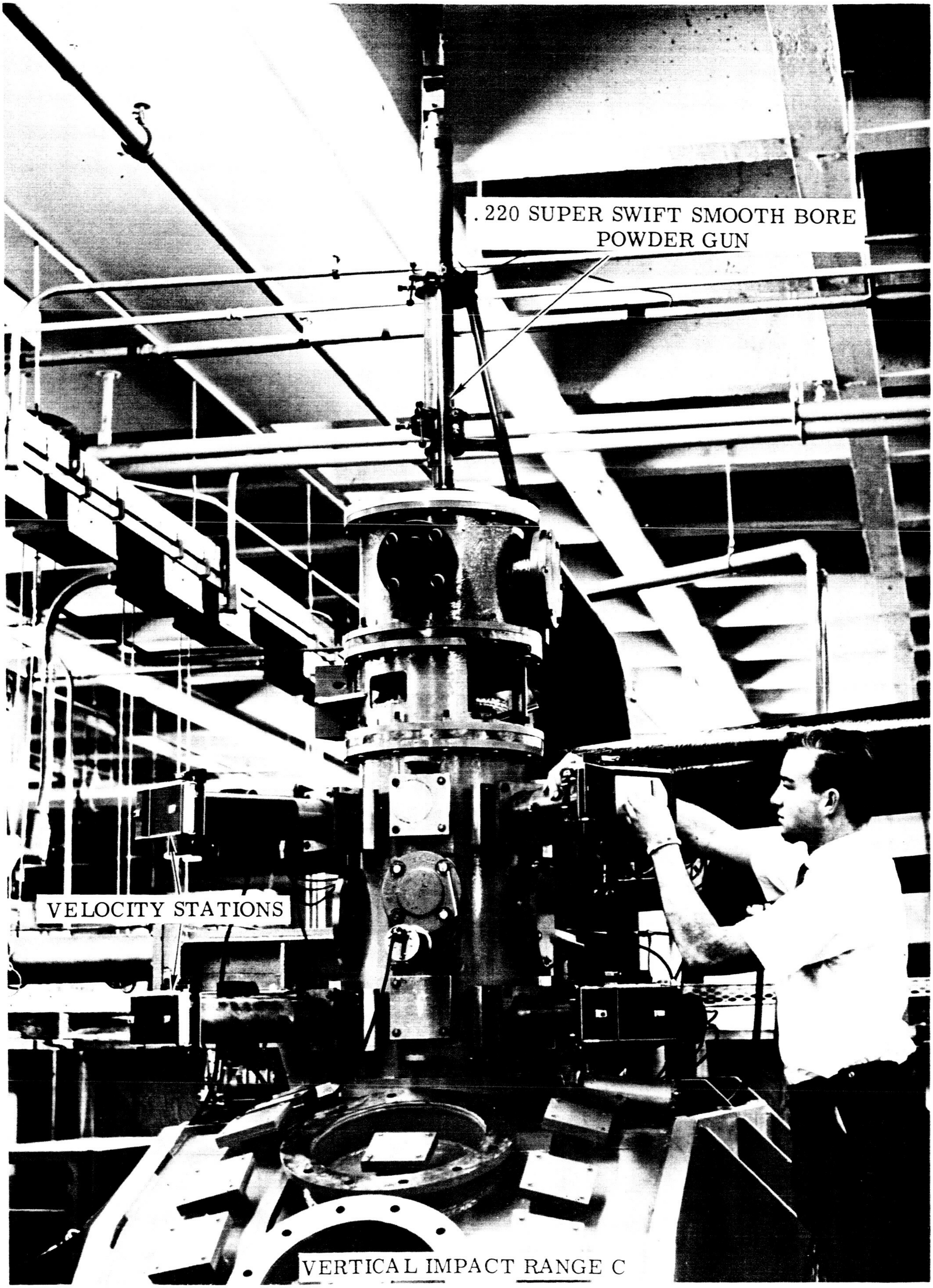


Figure 3 Vertical Impact Range

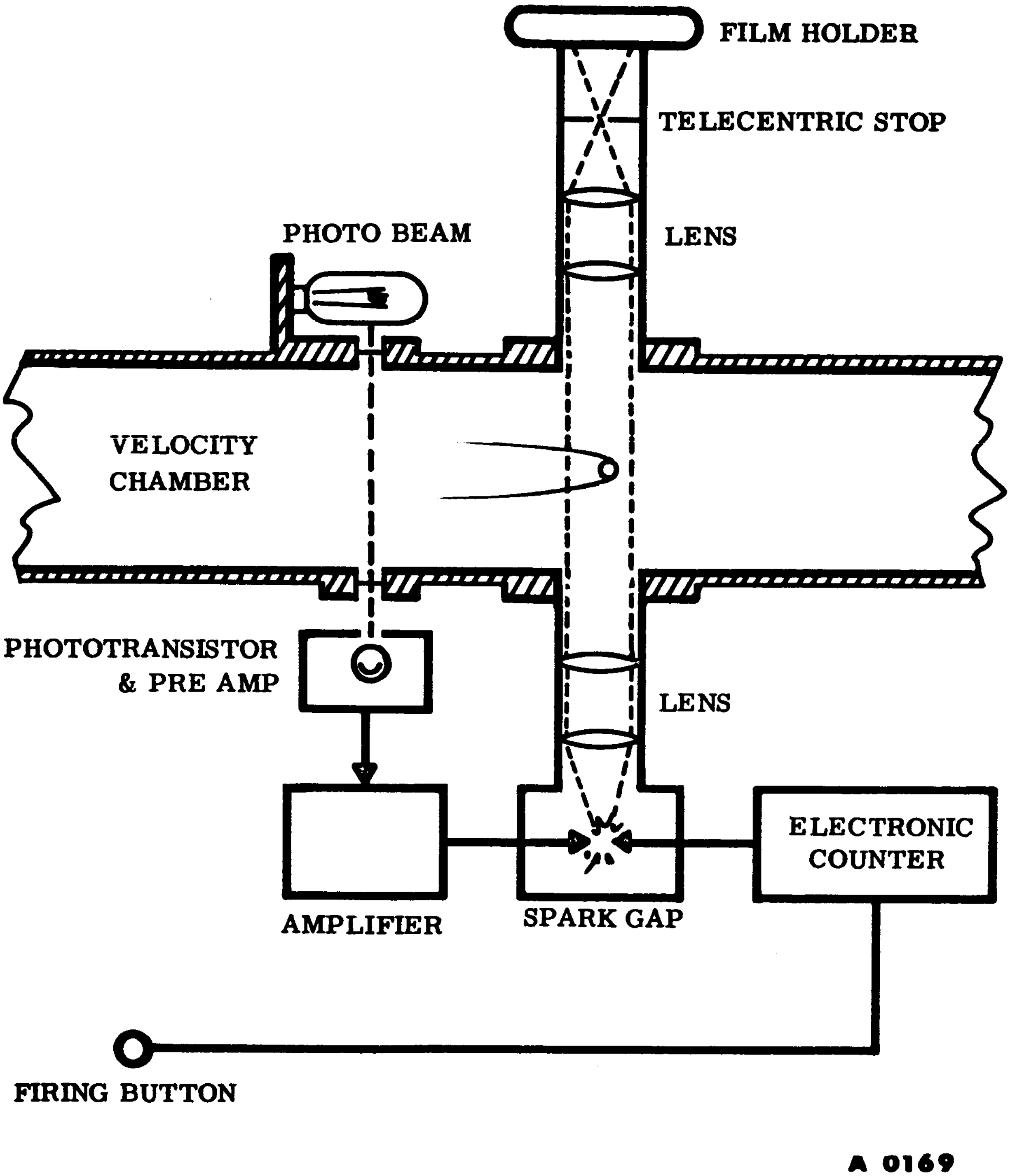
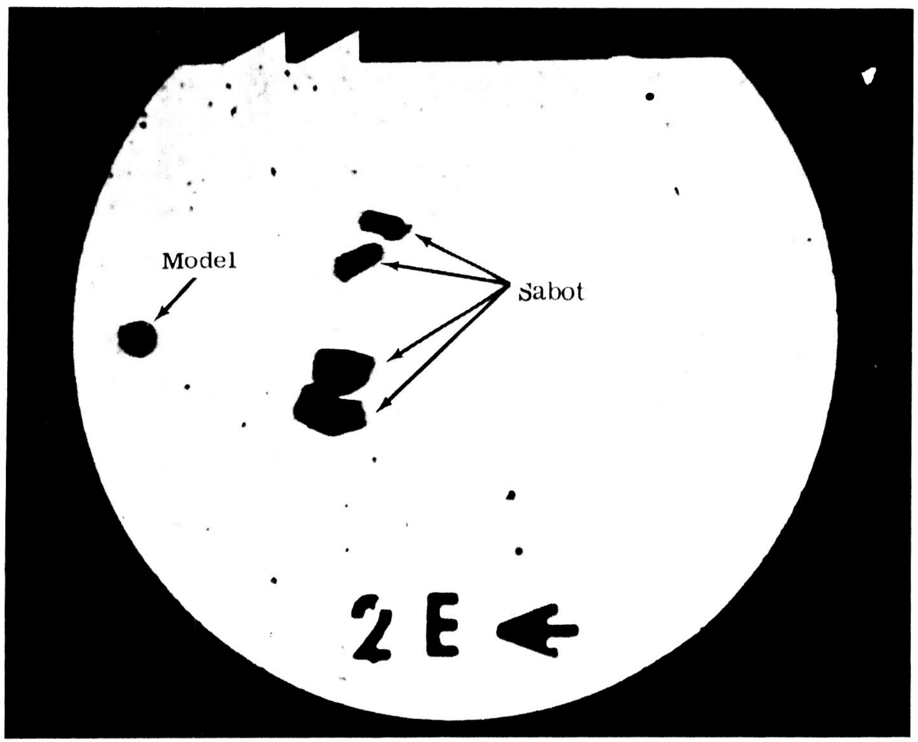


Figure 4 Schematic – Ballistics Range Velocity Station

Model Requirements: Saboting



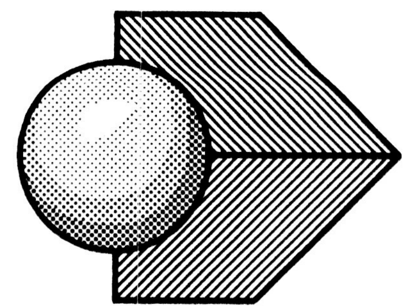
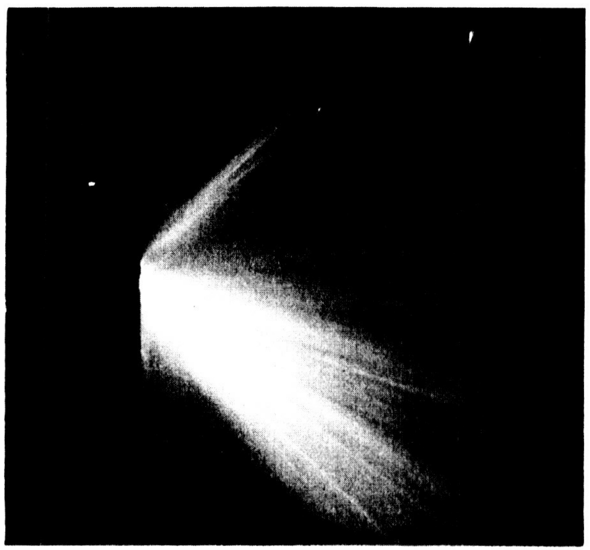


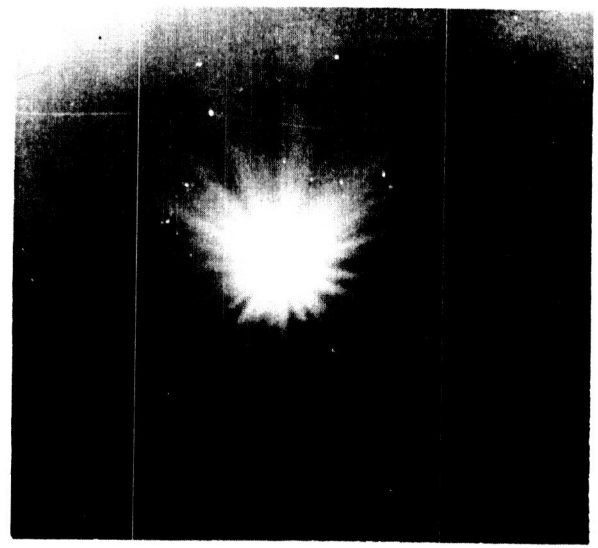
Figure 5 Typical Shadowgraph Showing Separation of Model and Sabot

Typical Impact Flash in Sand

SIDE



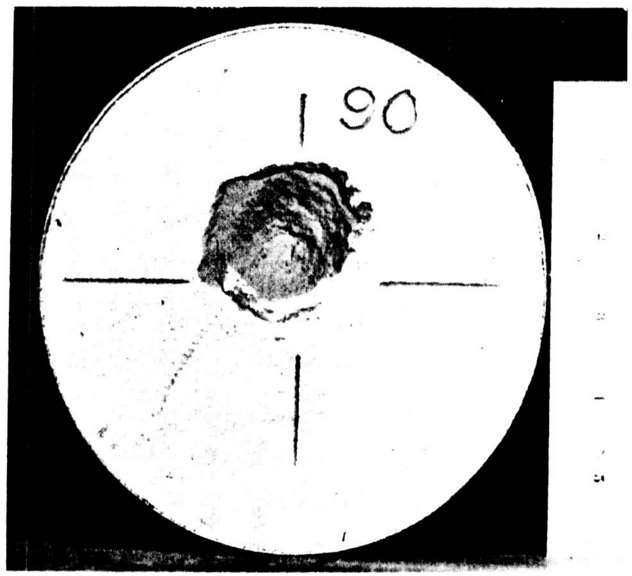
FRONT



V= 10, 360 ft/sec
P= 1mm Hg - AIR

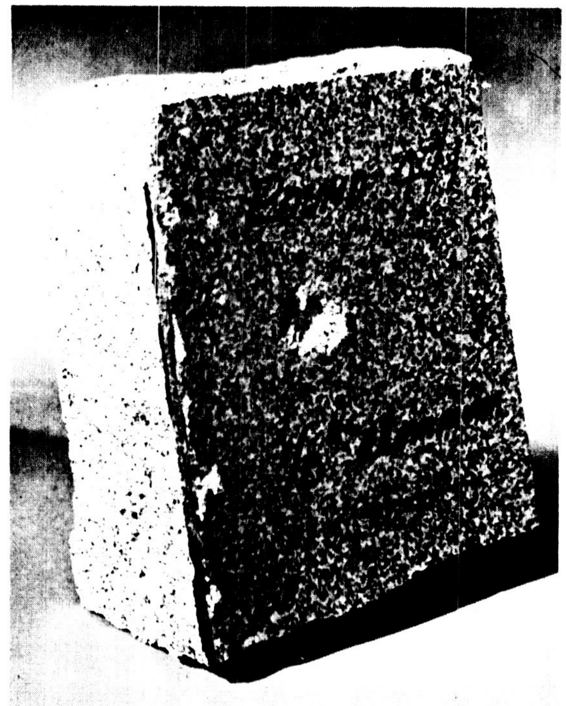
Figure 6 Typical Impact Flash in Sand

V= 8440 ft/sec
P= 1 mm Hg - AIR



SAND TARGET

V= 10, 360 ft/sec
P. 76mm Hg - AIR



GRANITE TARGET

Figure 7 Typical Impact Craters Formed in Sand and Rock

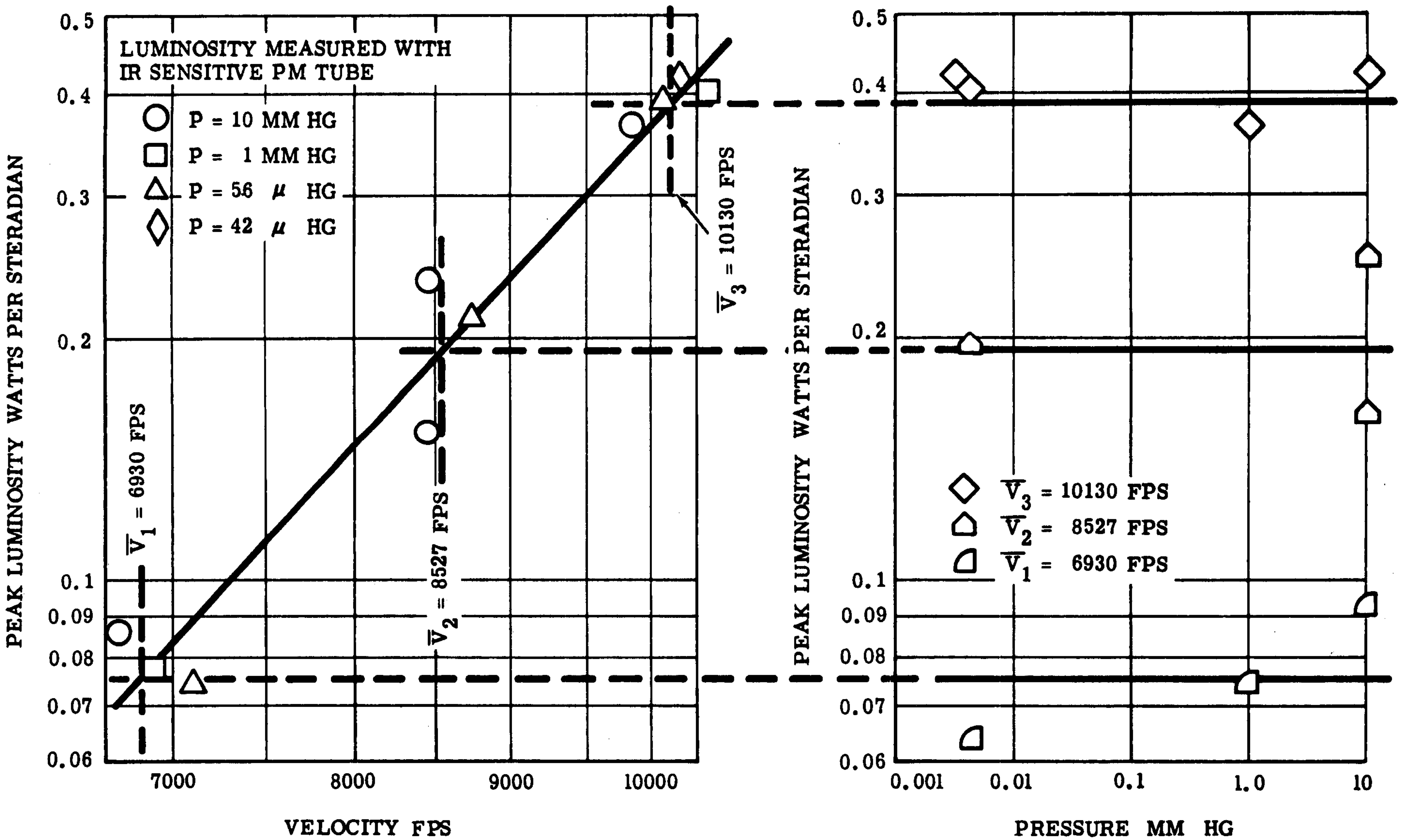


Figure 8 a.

Figure 8b

Figure 8 Effects of Velocity and Pressure on Peak Luminosity for the Impact of 0.22-in. Diam. Nylon Spheres on Sand Targets

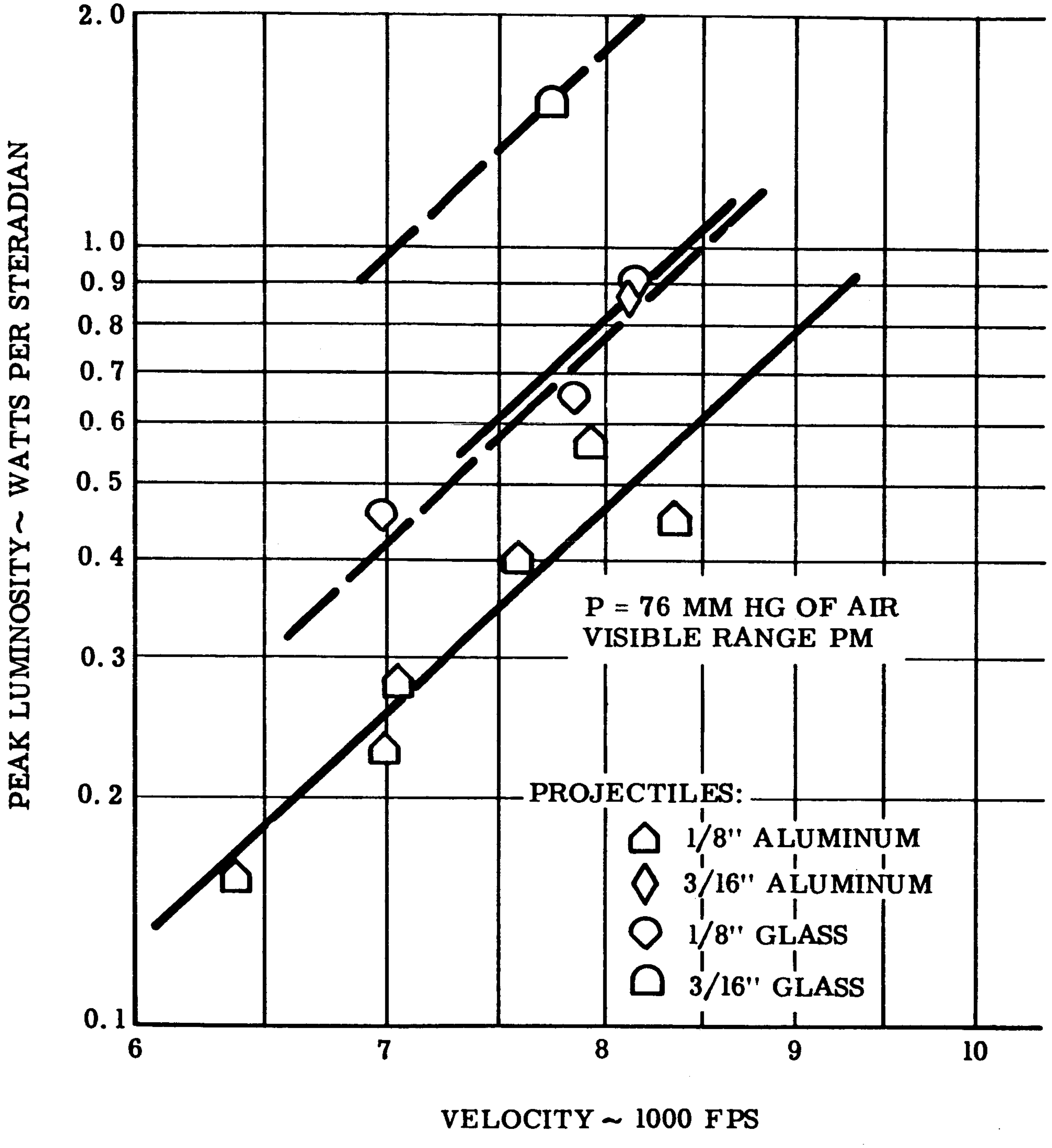


Figure 9 Peak Luminosity for Glass and Aluminum Projectiles Impacting Sand

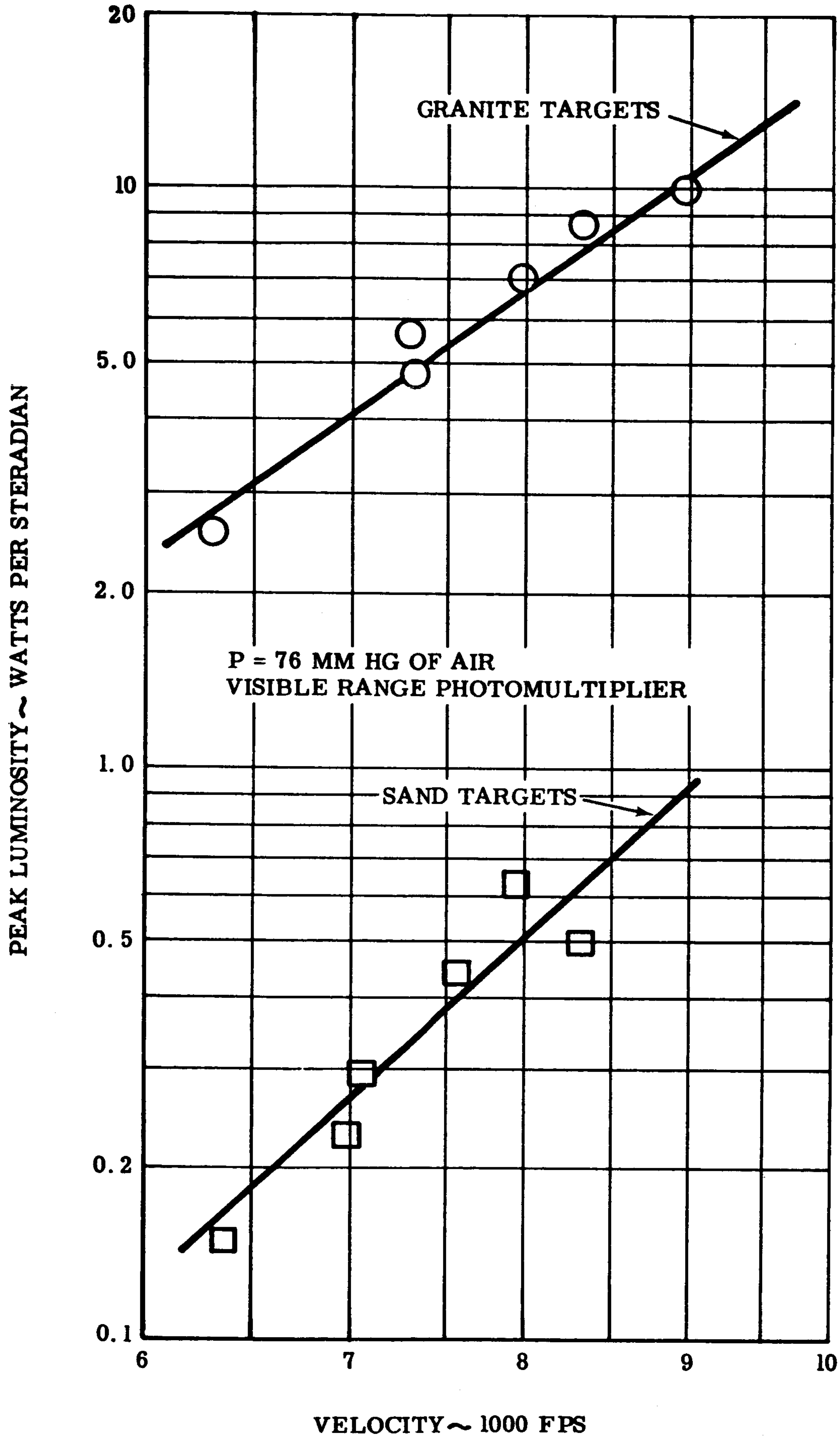


Figure 10 Peak Luminosity of 1/8-in. Diam. Aluminum Spheres Impacting Sand and Granite Targets

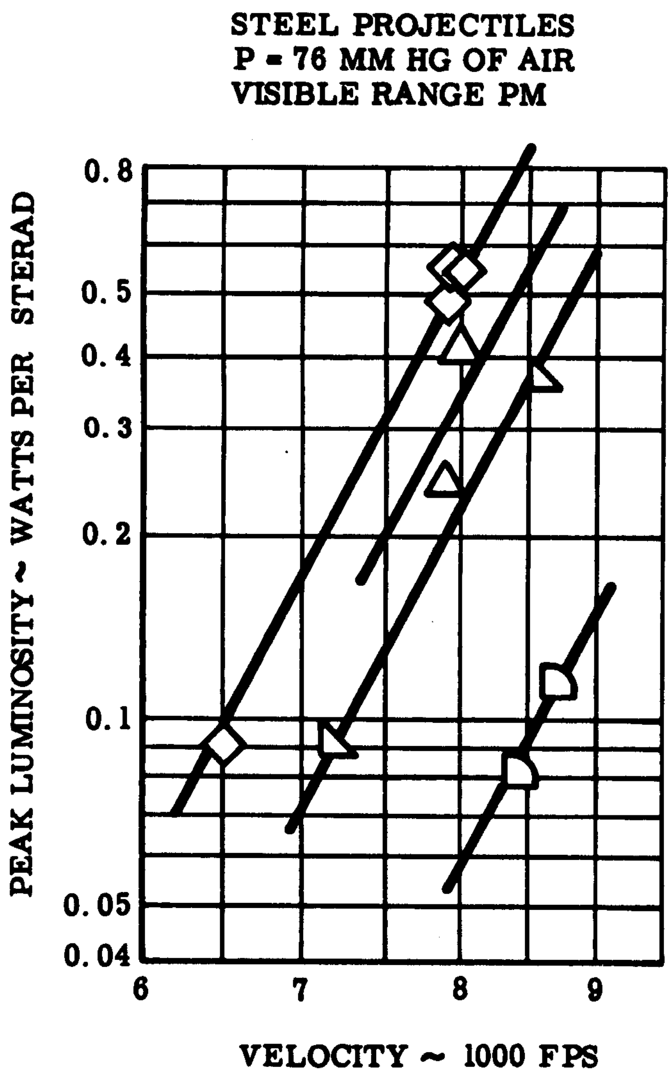


Figure 11a

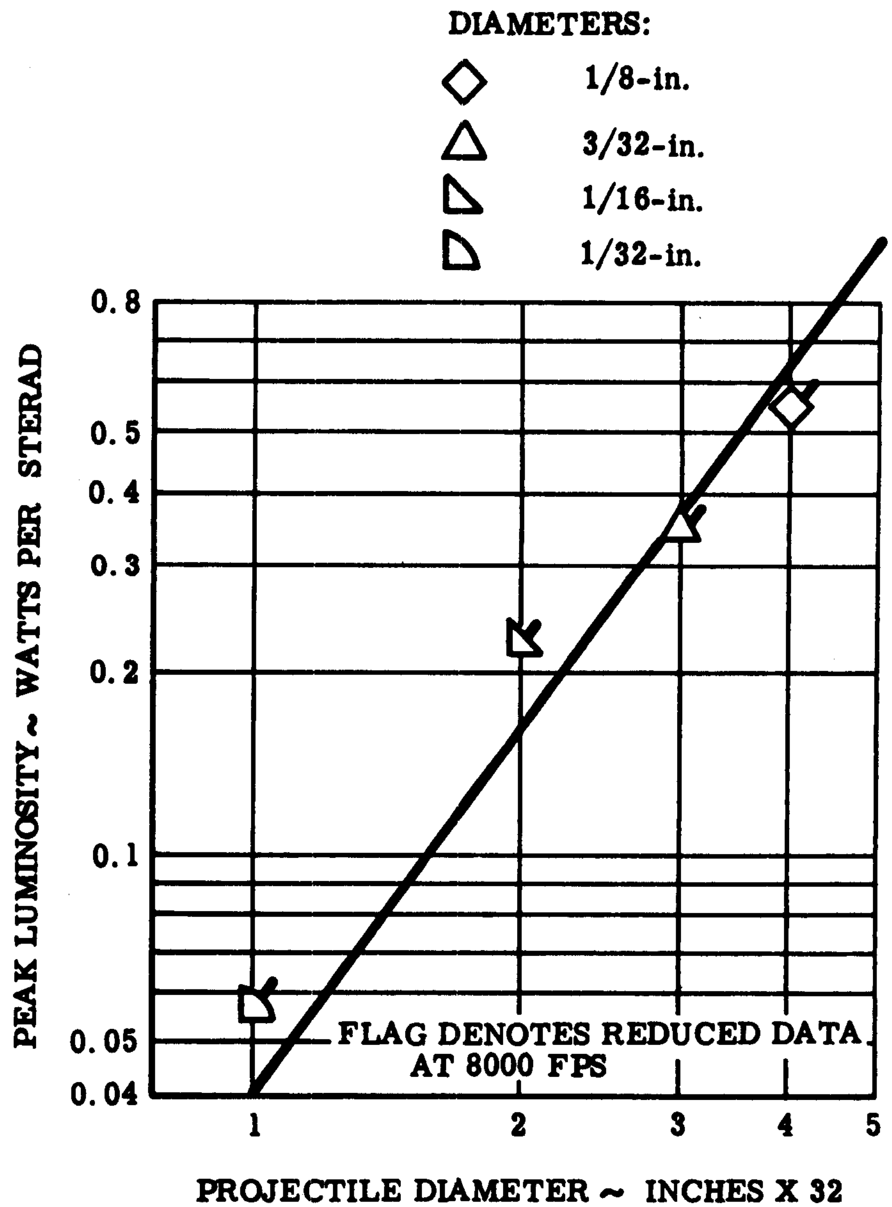


Figure 11b

Figure 11 Peak Luminosity of Various Size Steel Spheres Impacting Sand Targets

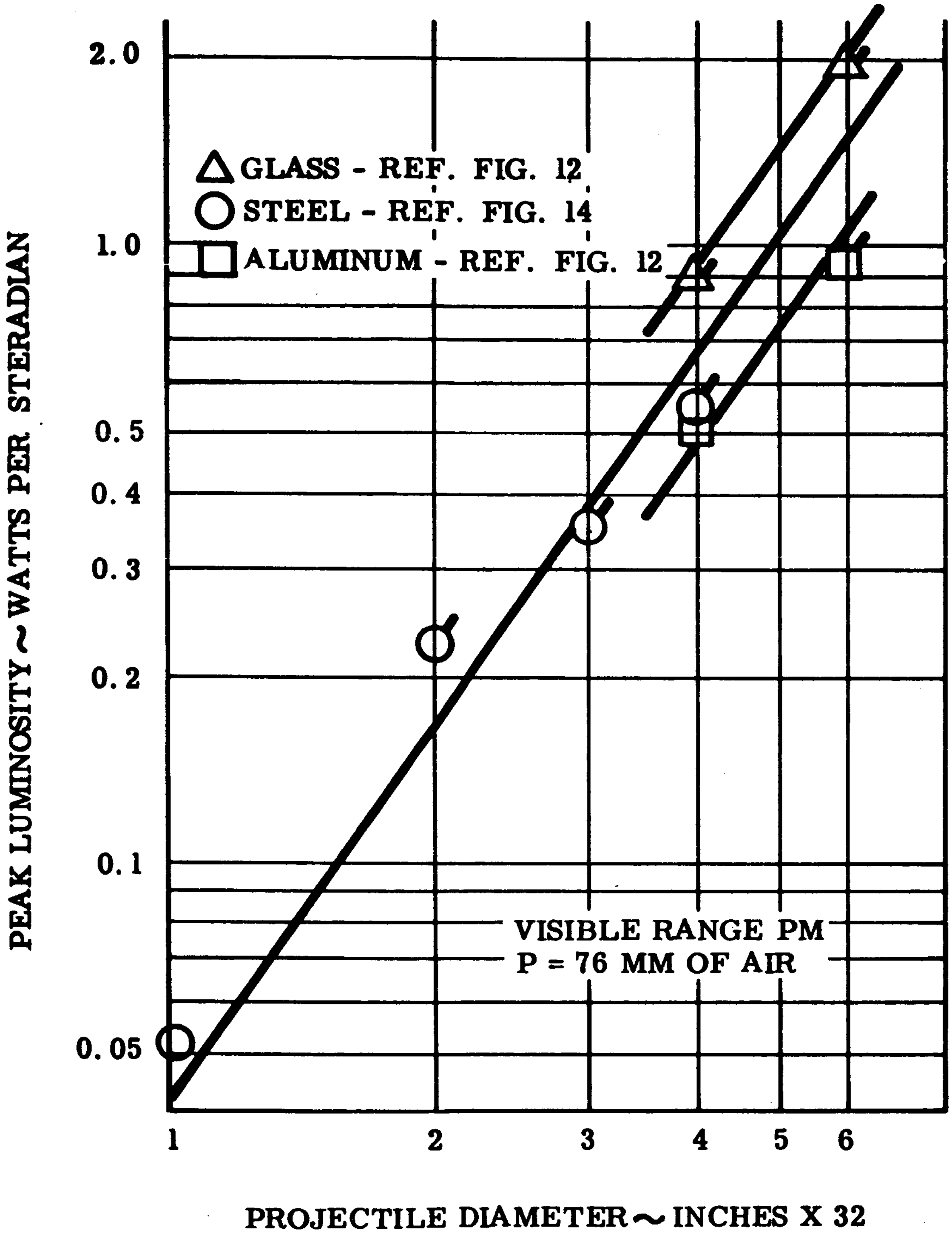
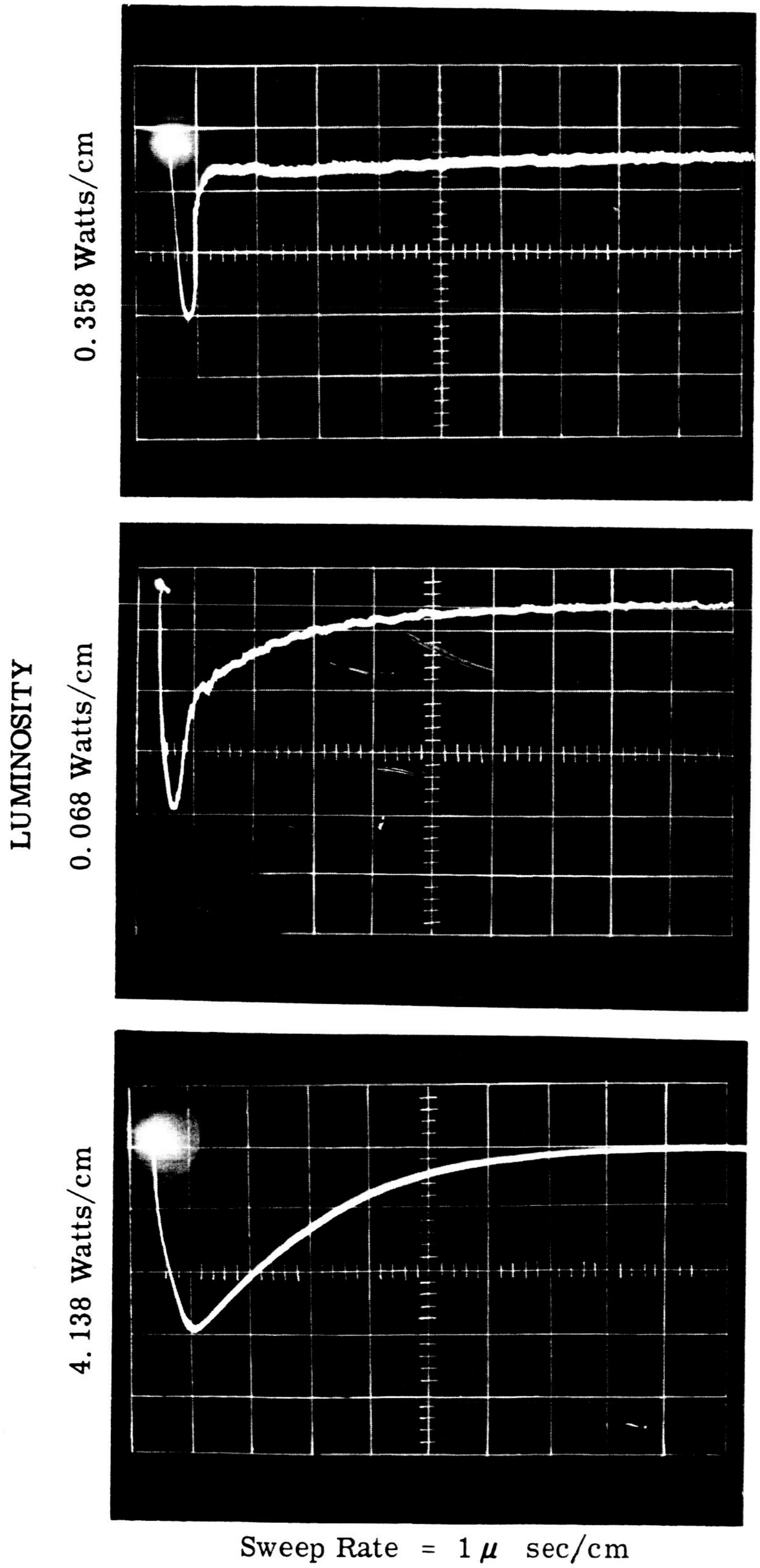


Figure 12 Reduced Data – Variation of Peak Luminosity with Diameter for Three Projectile Materials Impacting Sand at 8000 fps



1/8-in. Diam Steel Projectile
V = 8430 ft/sec
Sand Target

1/8-in.Diam Aluminum Projectile
V = 7730 ft/sec
Sand Target

1/8-in. Diam Aluminum Projectile
V = 8400 ft/sec
Polished Granite Target
(See Figure 13)

Figure 13 Typical Photomultiplier – Scope Traces for Impacts of Various Projectile/Target Combinations

Sequential Beckman-Whitley Photographs of a 1/8"
Glass Sphere Impacting an Aluminum Target at
23,000 Feet Per Second

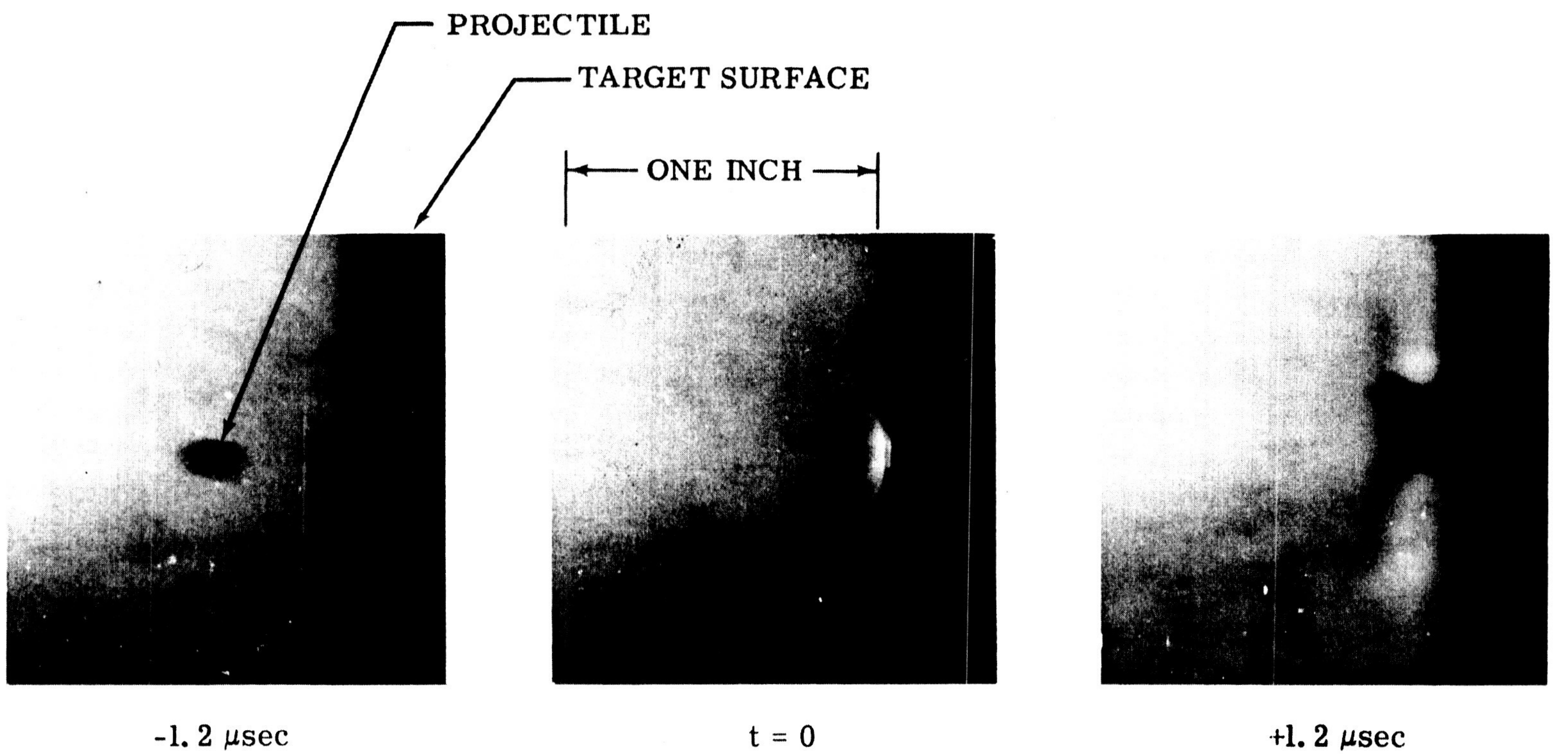


Figure 14 Sequential Beckman-Whitley Photographs of a 1/8-in. Glass Sphere Impacting an Aluminum Target at 23,000 fps

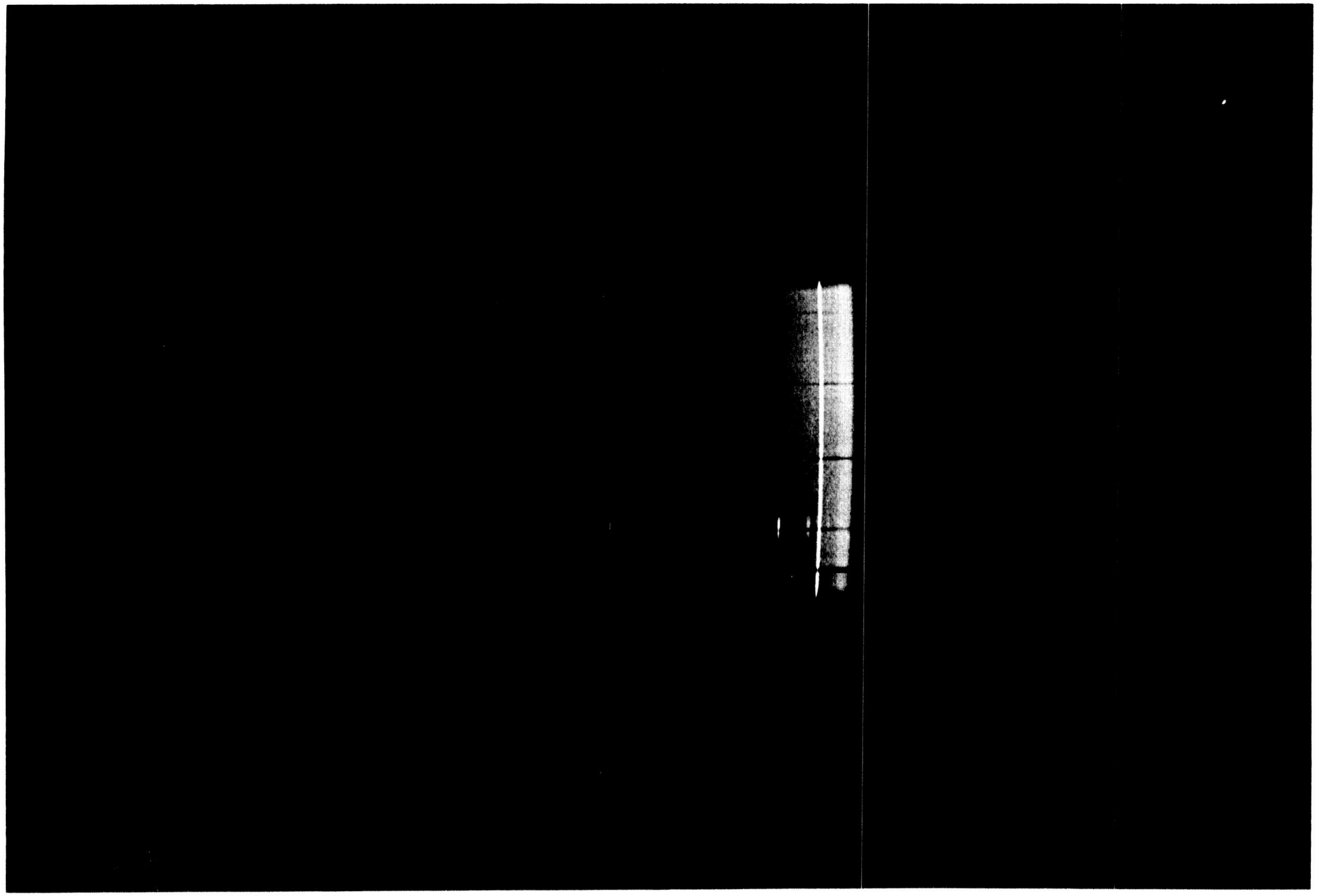


Figure 15 Spectrogram of Impact Flash Generated by Nylon Cylinder Impacting an Aluminum Target at 24, 600 fps

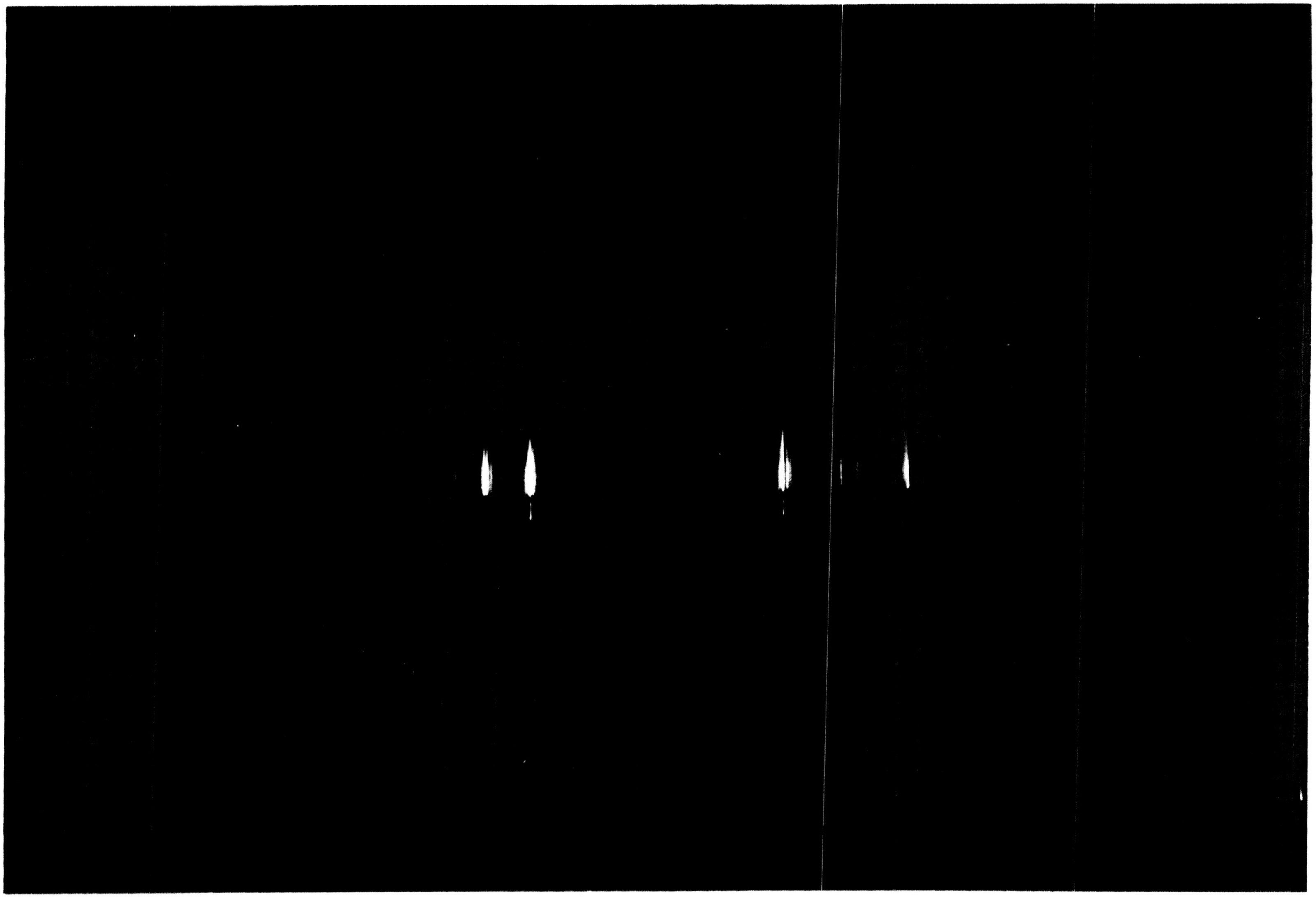


Figure 16 Spectrogram of Impact Flash Generated by Nylon Spheres Impacting Sand Targets at Approximately 10,000 fps – Ten Rounds Superimposed